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Variable Frequency Operation for Future Offshore Wind Farm Design: A Comparison with Conventional Wind Turbines

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Abstract

Recent developments of offshore power grid demonstrations in European waters at substantial distances from the onshore grid have accelerated the demand to look at high voltage DC power transmission (HVDC) as an alternative topology to traditional high voltage AC methods [1]. Current VSC-HVDC technology can realise the integration of a centralised power converter to control the speed of a cluster of turbines, thus reducing the number of power converters from the farm and therefore potentially increasing reliability and lowering power loss. This paper will primarily concentrate on the benefits of variable frequency operation of a wind farm using a centralised VSC-HVDC converter and comparing its performance to 50 Hz Type 4 wind turbines. The analysis will incorporate measured wind data form Irish offshore locations and will provide a detailed power loss methodology for the wind farm components with annual energy capture results for both variable and fixed frequency approaches.
Keywords:*, variable frequency operation, power loss, techno-economic comparison.*

1. Introduction

Future offshore wind farm developments present new challenges and opportunities as the choice of architecture is very much influenced by concerns of reliability and maintenance given the substantial distances involved from the onshore grid. One of the key considerations for this is the layout of the wind turbines and the different connection scenarios to the mainland grid.

Nomenclature

V/Hz	Voltage/Frequency
VF	Variable Frequency (20-50 Hz)
FF	Fixed Frequency (50 Hz)

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A recent paper by Madariaga et al. [2] discusses the technological trends and topology selection for future offshore wind development. It outlines the progressive trend for higher power turbines of up to 10 MW with full conversion capabilities, simplified gear box designs for lower maintenance requirements and different configurations of mixed AC and DC transmission topologies. The paper concludes that future offshore wind farm design will also utilise high levels of power electronics based DC interconnection between different wind sites and the onshore grid. In 2011 Nedic et al. [3] from Siemens UK and with the University of Manchester presented a software tool for automating both the design and cost benefit analysis for offshore wind farm design. The software includes load flow analysis, cable sizing, reactive power compensation calculations and approximate costings for different layouts. The paper focuses on the overall software design that includes models for loss sources such as cables and transformers, as well giving details on reactive power requirements required.

The reliability of the power electronics over time is still a key concern both at the wind turbine level and for the HVDC conversion. A comprehensive reliability study by Hahn et al. [4] taken over a 15 year period for 1500 wind turbines showed the power electronics to have the highest annual failure rate within the turbine sub-system. From this perspective it could be concluded that future offshore wind farms will require lower levels of power electronics to increase farm reliability and also reduce maintenance costs. Recent literature has seen a number of studies looking to investigate alternative offshore wind farm architectures that require less power electronics and utilise robust generator configurations. One approach which has been proposed is the use of a single centralised converter which controls the variable speed of a cluster of wind-turbines that eliminates the converter from each turbine. This approach uses a variable voltage and frequency, but fixed voltage to frequency ratio, (V/Hz) wind farm collector grid with a VSC-HVDC connection from offshore to onshore [5][6]. For this V/Hz approach a cluster of turbines are controlled centrally and therefore each individual turbine within a cluster may have a non-optimal energy capture when compared to individually optimised Type 4 wind turbines. Gevorgian et al. investigated the annual energy capture of the variable frequency approach with Type 1 turbines with a centralised converter compared to conventional Type 4 wind turbines [7]. As would be expected the conventional turbines offer higher levels of energy production, however for wind sites with lower wind speed diversity, characteristically of offshore sites, the inter-turbine wind speed diversity was found to be approximately less than 1 m/s equating to less than 3% annual energy difference between both approaches according to the authors. A recent study by Parker et al [8] explores the cost and losses associated with offshore wind farm configurations which have a centralized power electronic converter. DC and AC wind farm configurations are considered along with standard string topologies for the comparison. DC topologies were found to have a lower cost and loss than AC, but the authors commented that the lack of commercially available converters makes the advantage less certain in the short to medium term. A further interesting study by Dominguez-Garcia et al [9] explores the effect of non standard operating frequencies on the economic cost for offshore AC networks. The paper again suggests connecting several wind farms to multiple HVDC links (*SuperNode* concept) that may be operated at a variable frequency from 20-120 Hz and the authors focus on the frequency cost scaling of the wind farm components. A case study is presented for an actual wind park location where a minimum point in the total cost of the offshore network is found to be 93 Hz. The paper concludes higher operational frequency could have potential long term benefits with transformer volume reduction and lower power loss and also economic payback advantages. However, the authors acknowledge more detailed technical/economic models are needed to fully verify these concepts. Although previous works have focused on characterising the potential loss of energy due to non-optimised wind capture, clearly this loss has the potential to be offset by savings due to the elimination of the power converter from individual wind turbines.

This paper will investigate if reduced losses in the wind farm architecture with V/Hz operation can offset the losses incurred due to non-optimisation of wind capture of individual turbines and under what circumstances this approach may be considered for an offshore wind farm. The analysis primarily concentrates on the benefits of low frequency operation (<50Hz) for losses in individual wind farm components, such as the cables, transformers, and converters. Reducing the number of power converters from the farm may also increase reliability, lower power loss and reduce overall investment and maintenance costs. Two offshore locations with measured wind data sets are used to explore energy capture and power losses with both fixed and variable speed operation. A techno-economic comparison will also be included to highlight the financial implications/direct comparison of both approaches.

The paper is structured as follows: Section 2 of the paper introduces the methodology of the V/Hz approach. Section 3 presents the models to calculate the power loss contribution of the wind farm components. Section 4 will provide the comparison and results of the variable frequency design to traditional fixed frequency approach, providing a detailed loss breakdown and cost comparison. Finally Section 5 will discuss the outcomes of the study and comment on the viability and technical merit of variable frequency operation for future offshore wind farm development.

2. Methodology

2.1. V/Hz Operation

A wind farm with a single VSC-HVDC converter with variable frequency operation looks to find the optimum operation point by adjusting the wind farm collector offshore grid frequency for a cluster of wind turbines. For generators and transformers to operate under this scheme they must be controlled with a constant V/Hz ratio – when the frequency of the overall system changes, the voltage must also change at the same rate to keep the ratio constant. The turbines are directly connected to a single centralised VSC-HVDC converter maintaining speed control for the entire cluster. The scheme is suitable for brushless machines such as SCIGs (Squirrel Cage Induction Generators) and PMSG (Permanent Magnet Synchronous Generators). A V/Hz control block will be located at the VSC-HVDC station, see Fig.1. [10].The V/Hz controller looks to maximise power from the available wind, to operate a number of turbines at their maximum power coefficient C_p. The system operates as follows:

1. Wind speed is measured at each turbine and averaged and this value is communicated to the V/Hz controller at the offshore VSC station. The control firstly sets the reference speed, from the wind by:

$$\omega_{ref} = \frac{V_W}{Tip\_Speed\_Ratio\_Const} \tag{1}$$

2. The reference speed term is then used to set the frequency:

$$f_{set} = \frac{\omega_{ref}}{2\pi} * 314 rad/\sec \tag{2}$$

3. Finally, the voltage is set as:

$$v_{set} = \frac{V_{LL}\_gen\_rated}{\omega_{rated}} * 2\pi f_{set} * Traffo\_Winding\_Ratio \tag{3}$$

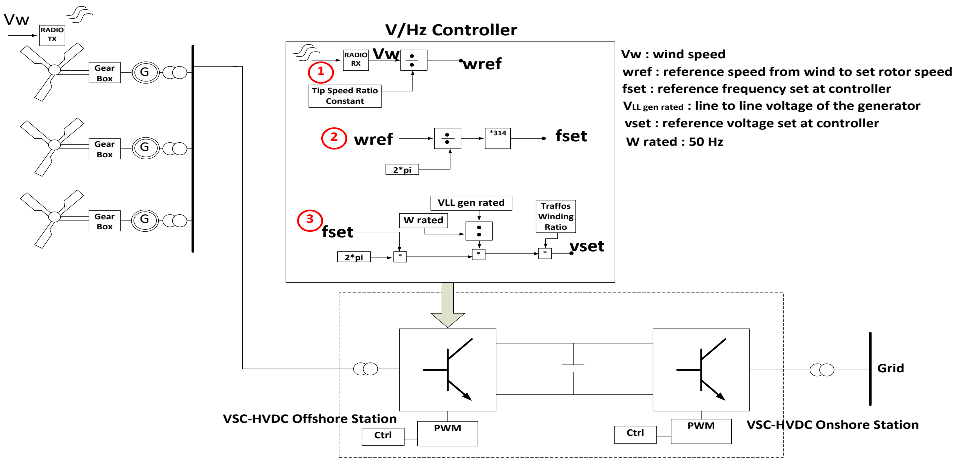

Fig.1. System operation of V/Hz control

2.2. Variable Frequency Operation with Measured Wind Data

The frequency scale for V/Hz operation with wind speed is depicted in Fig.2 (a). Above rated frequency of 50 Hz the voltage and frequency are fixed and below rated to cut-in the voltage and frequency are both variable. The system ratings are for a typical wind turbine– cut in is at approximately 20 Hz for 4 m/s and rated power is set to 50 Hz for 13 m/s.

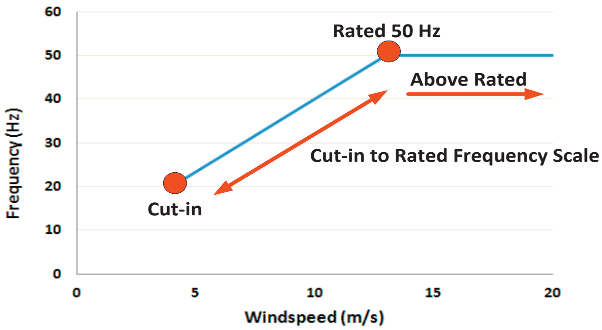

Fig.2. (a) Variable frequency operation for wind turbine (b) M4 and M5 locations used for the study (Image courtesy of Google Earth)

Clearly the amount of time the system operates at a particular frequency depends on the wind speed distribution at a certain offshore location. Measured wind speed data is utilised to demonstrate the potential of the offshore wind resource in Ireland and also evaluate the performance of the variable frequency wind farm design to conventional Type 4 wind turbines with individual full converters. The wind data employed for the analysis is provided by the Irish Marine Institute [11]. The institute has a number of measurement buoys around the Irish coast measuring average hourly wind speed using anemometer data [12]. Two offshore locations are selected for the analysis here with two years of wind data – buoy site M4 off the northwest and M5 off the southeast coast – both sites have approximately 95% of the total annual data set. Other buoy locations lacked consistent data due to operational problems common to such devices located in exposed sea locations and so are not included in the study. The wind speed measured at the buoy is taken just above the surface of the water and is converted to the correct hub height wind speed typical for offshore turbines.

The annual turbine operational range at different frequencies for both buoy locations is displayed in Fig.3 Reviewing this analysis it is clear that the wind turbines will operate in V/Hz range for long periods of the year for both offshore locations. For wind speeds above rated turbine operation, both the V/Hz approach and conventional turbines produce equal power. However, for the variable frequency approach the wind farm will be operating below rated (<50Hz) between cut-in and rated wind speed for significant periods of the year. Here, there is potential for annual energy savings associated with reduced power losses for the individual wind farm components.

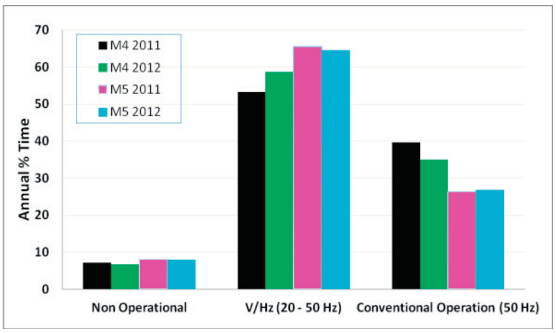

Fig.3. Frequency range of turbine operation for two offshore locations 2011/2012

3. Wind Farm Design and Component Loss Calculations

3.1. Wind Farm Layout

The offshore layout for the study is given in Figure 4. The indicative layout of the offshore wind farm is taken from a previous study presented by Badran et al. [13]. It consists of one hundred 2 MW wind turbines arranged in 10 rows of 10 turbines and the approximate distance layout of the farm components is displayed in Fig.5. The wind turbine has a transformer that converts the generator voltage of 690V to 33kV for transmission using submarine XLPE cables [14]. The 33kV cable is tapered and is arranged in a string type configuration, see Figure 4. The offshore platform hosts a 33kV/220kV transformer and a VSC-HVDC converter station - these components are not included in the loss analysis, as both are utilised in the V/Hz and conventional wind farm design.

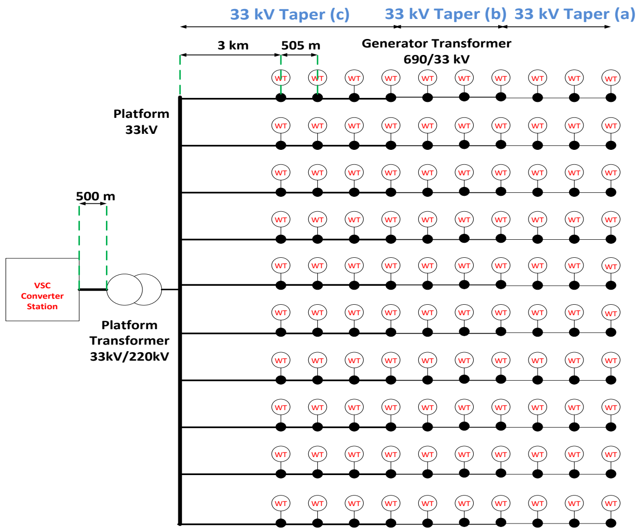

Fig.4. Proposed layout of the wind farm for the study

3.2. Cable Loss

The collection and transmission cables are a key component of the wind farm architecture. The generator to collector transformer cable is rated for 33 kV and the connecting cable to converter is rated in this case for 220 kV, see Table 1 for specific cable parameters. The 33 kV cable is tapered with 3 different cross-sectional areas to transmit the power to the offshore substation. The electrical behavior of the cables are modeled using the standard π equivalent circuit. The work by Funaki et al. [15] proposes low frequency AC transmission to lower losses in the transmission cables. The charging current of the cable, I_c reduces with decreasing frequency and is expressed using the following expression:

$$I_c = 2\pi fClV \tag{4}$$

Where: f: frequency (Hz), C: capacitance (F), l: length of the cable (m), V: voltage (V)

The ohmic losses P_Ω are expressed using equation (5):

$$P_\Omega = I^2 R \tag{5}$$

Where: I: current per phase (A), R: resistance (Ω/m)

The dielectric losses for the cable are associated with the dielectric insulation material. It acts as a capacitor when it is subjected to alternating current. The dielectric loss, W_d, for a cable under AC operation is expressed as:

$$W_d = 2\pi f C V^2 \tan\delta \tag{6}$$

Where: f: frequency (Hz), C:capacitance (F), V: voltage (V), $tan\ \delta$:insulation loss factor (0.0004 - XLPE)

Table.1. Cable Parameters [14]

Voltage	R/Ω.km	X/Ω.km	C/nF.km	Total Length of Cable for Farm (km)
33 kV (Taper (a) 120 mm^2)	0.153	0.137	183	15.15
33 kV (Taper (b) 240 mm^2)	0.075	0.125	229	15.15
33 kV (Taper (c) 500 mm^2)	0.730	0.113	298	45.15
220 kV (Taper 1200 mm^2)	0.046	0.07	198	0.500

3.3. Transformer Loss

A 0.69/33 kV transformer model is developed to provide indicative losses for both the core and the conductive (winding) losses – full load efficiency of transformers is assumed to be approximately 98% at 50Hz. The Steinmetz equation is the classical method to calculate the transformer core loss. From previous literature core loss is taken as approximately 1/6 of overall transformer loss at 50 Hz [16], and from this a ratio of core power loss can be approximated taking the α exponent from Steinmetz at lower frequencies using equation (7):

$$\left(\frac{P_{f1}}{P_{f2}}\right) = \left(\frac{f_1}{f_2}\right)^{\alpha} \tag{7}$$

Where: P_{f1}: power loss at 50Hz, P_{f2}: power loss at required frequency, f_1:50 (Hz), f_2: required frequency (Hz), α: exponent of flux density – electrical steel [1.8-2.2].

The DC conduction losses are taken as I^2R_{dc} and are the dominant loss source for the transformer. The AC conduction losses are assumed to be negligible at frequencies lower than 50 Hz and are not included in the model [17]. Figure 5 shows the loss breakdown for the total 100 wind turbine transformers with respect to frequency – the dominant loss source is the conduction loss of the windings with an increase in load while the core loss only marginally increases over the 20-50 Hz range.

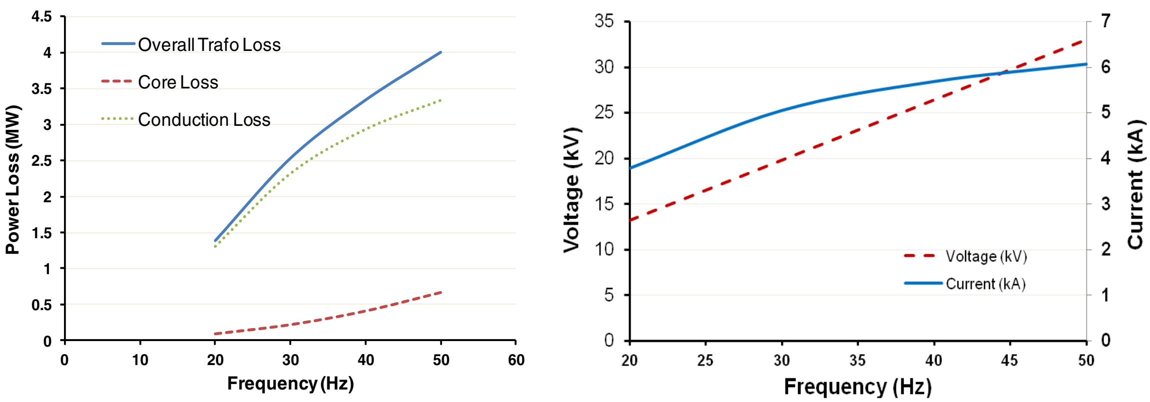

Fig.5 (a). Power loss distribution of the 100 wind turbine transformer (b)V/Hz ratio with load current for 100 transformers

As the frequency decreases the voltage also decreases to keep a constant V/Hz ratio. However, the load current does not reduce at the same rate as the V/Hz ratio, see Figure 5 (b), therefore the I^2R conduction losses of the transformer dominate with respect to the core loss over the frequency range.

3.4. Converter Loss for Type 4 Wind Turbine

The variable frequency approach is evaluated against a conventional Type 4 wind turbine with a full power converter. A curve fit of power losses for the converter at varying load is taken from the analysis presented by Tamura [18] who presents a detailed power loss breakdown of the entire PMSG wind turbine architecture including the power converter.

4. Results

The performance for both the variable frequency and fixed frequency 50 Hz conventional wind farm approach for 2 offshore site locations with measured wind speed data for the years 2011 and 2012 is now presented. The results concentrate on 3 key performance aspects:

1. Annual power loss breakdown for individual wind farm components including total annual energy output
2. Infrastructural cost comparison

4.1. Variable Frequency – Conventional : Annual Power Loss and Energy Performance

Table 2 presents the detailed loss breakdown for both offshore sites for the years 2011/2012 –the table includes losses for the cables and transformers and provides the total annual energy for both systems. The fixed frequency system (FF) includes the loss associated from each wind turbine power converter, described in Section 3.4. The variable frequency system (VF) includes the loss associated with the non-optimum power capture. The non-optimum power capture calculation is taken as 2% of the total potential annual energy capture of the site which was presented by the work in Gevorgian et al [7] – for offshore wind sites with lower wind speed diversity the inter-turbine wind speed diversity was found to be approximately less than 1 m/s, equating to less than 3% annual energy difference between VF and FF. Figure 6 (a) shows graphically the power loss breakdown for each site and year for both approaches.

Table.2. Power Loss Breakdown at the Offshore Sites

Site Location and Year **[200 MW]** **FF** : Fixed Frequency 50 Hz **VF** :Variable Frequency	**Cable Loss (MWh)**	**Trafo Loss (MWh)**	**Converter Loss (MWh)**	**Non Opt Wind Capture (MWh)**	**Total Power Loss (MWh)**	**Total Annual Energy (MWh)**
M4 2011 FF	**43200**	**20998**	**70786**	**-**	**134983**	**1005067**
M4 2011 VF	**50650**	**24709**	**-**	**22801**	**98160**	**1041890**
M4 2012 FF	42310	20575	68839	-	131724	995976
M4 2012 VF	50377	24598	-	22554	97529	1030171
M5 2011 FF	**36925**	**17995**	**58916**		**113836**	**893564**
M5 2011 VF	**46046**	**22529**	**-**	**20148**	**88723**	**918677**
M5 2012 FF	37514	18275	60008	-	115798	903152
M5 2012 VF	46363	22678	-	20379	89419	929531

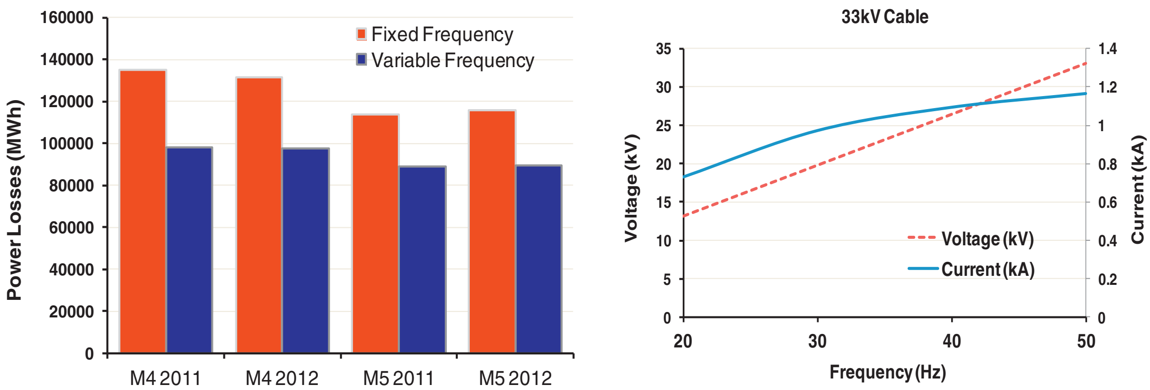

Fig.6 (a). Power loss breakdown for 2 sites (b) V/Hz ratio with current in the 33kV cable

Reviewing Table 2 the variable frequency approach shows higher power losses for both the cables and transformer, due to the phase current for the I^2R losses not reducing at the same rate as the V/Hz ratio. Figure 6 (b) shows this for the 33kV cable, with the phase current not reducing with frequency at the same rate as the voltage. However, the individual converters for the fixed frequency wind turbines have a significant contribution to the loss calculation. The overall total annual energy difference between both approaches for each site is significant, ranging from 2.7% to 3.5 % greater total annual energy for VF over FF for M4 in 2011 – see Table 2. The VF operation has lower power loss and higher total annual energy for both sites in 2011/2012. Also, the performance of the VF approach is site specific – annually M5 spent a greater percentage of time in the variable frequency range, Figure 7 demonstrates this by showing the distribution of the annual wind speeds for the operating regions of each location in 2012 – highlighting M5 as a more suitable location for a VF operated site.

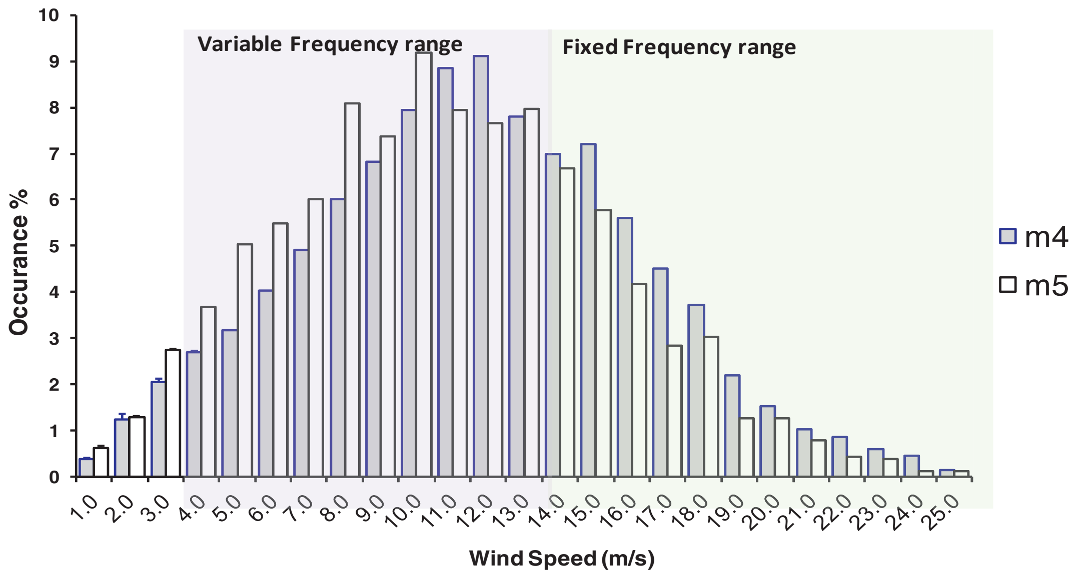

Fig.7. Mean wind speed distribution for both sites in 2012

4.2. Variable Frequency – Conventional : Capital Cost Comparison

The installation component costs for the wind farm design are given in Figure 8 – the costs are sourced by the recent 2013 paper by Parker et al [8]. The indicative costs show the VF approach at a lower cost given the substantial contribution of the wind turbine converters for the FF approach. Figure 9 gives a breakdown of the total losses in terms of cost per (€) for each approach for site M4 in 2011. The cables for the VF approach are the dominant cost loss source while as expected for the FF the converter loss has the biggest contribution. Annually, the FF approach has 27% greater losses in terms of power loss (€) than VF.

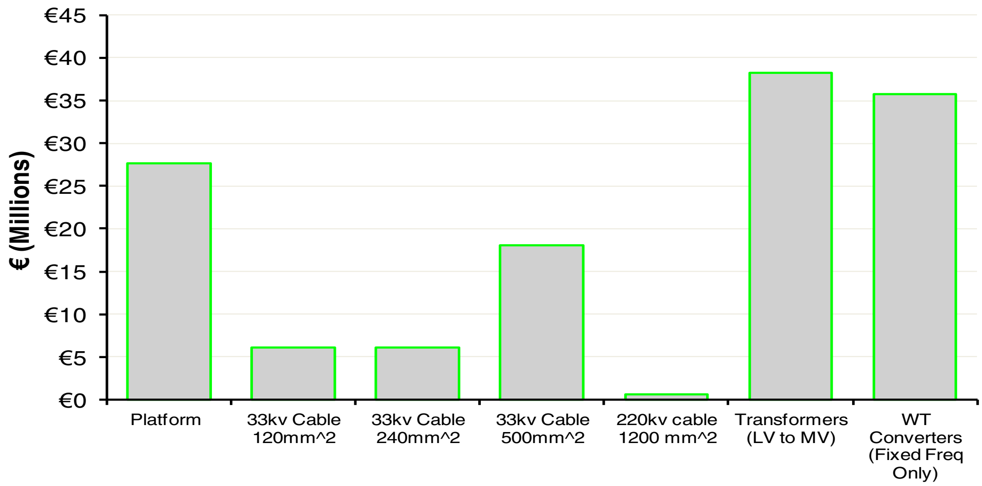

Fig.8. Cost breakdown for the capital installation of the wind farm (excludes wind turbines)

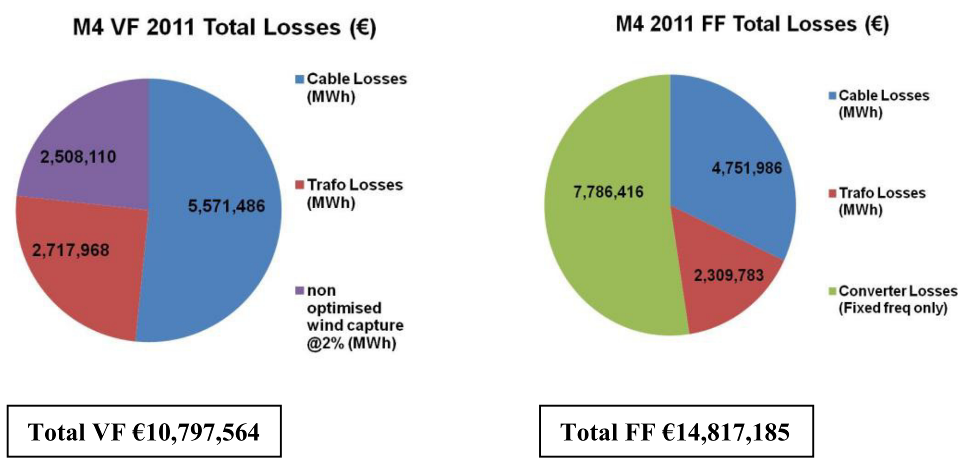

Fig.9. Cost of the loss sources for variable and fixed frequency

5. Conclusion

This paper has presented a detailed analysis of a variable frequency operated wind farm and compares its performance to a conventional fixed frequency wind farm with Type 4 wind turbines. The VF approach has lower power losses and greater energy capture of up 3.5% when compared to FF for two sites for the years 2011/2012. Analysing the power loss breakdown of the individual components of the wind farm its clear the VF approach has higher power losses for both the cables and transformers, due to the load current not reducing at the same rate as the V/Hz ratio. However, the dominant loss source for the FF is the converter accounts for approximately 52% of the overall losses for the FF scheme when compared to approximately 23% for non optimum power capture loss of the overall losses for the VF. The optimum operating strategy (VF or FF) is also site specific - if the offshore location has higher than average wind speeds then FF is more favourable. However, with a large variation in wind speed the non optimum power capture loss can increase, possibly causing FF to have a higher total energy export from the wind farm. Further work is needed to fully understand the non-optimum power capture calculation and also examine the impacts of wind farm layout including wake effect on energy capture variation.

Reliability and cost are also key metrics to consider, the FF design has a large density of power converters at the farm, increasing both the capital installation and maintenance costs. The VF design utilises the already existing VSC-HVDC station and the concept has the potential for less maintenance and lower levels of power electronics failures [4].

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